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Relativistic Nuclear Collisions Program

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The RNC Program is carrying out, analyzing, or planning experiments studying the collision of heavy ions over a large energy range: (i) the Bevalac, where nuclear matter is compressed sufficiently to study its equation of state; (ii) the AGS at BNL, extending the studies of the Bevalac to an energy range where the maximum pressure from the baryons is likely to occur; (iii) the SPS at CERN, where the energy density of the *nucleons* in the collision of very heavy nuclei may be sufficient to produce a phase transition to a plasma of free quarks and gluons in a baryon-rich environment; and (iv) RHIC, where the energy density of the *produced particles* will be sufficiently high that production of the quark-gluon plasma is expected to occur. Understanding the reaction dynamics of nuclear matter and its equation of state is of fundamental interest.

Analysis of the Bevalac experiments, the Dilepton Spectrometer (DLS) and the EOS Time Projection Chamber (TPC) is almost completed. The analysis of the data from two periods of running at the AGS with the E895 experiment (EOS at the AGS) is in process and producing interesting results. Beginning in 1998, the RNC group will no longer participate in data taking runs of CERN experiment NA49 and is concentrating only on the data analysis. The main focus of the high-energy heavy-ion research program at LBNL is the STAR experiment at RHIC, which will begin data-taking in 1999.

The RNC Program has broadened its physics base by starting the peripheral collision physics program within STAR. For heavy ions at RHIC the luminosity for photon-photon interactions in peripheral collisions is very high so that an extensive program of meson spectroscopy becomes possible. At the same time Pomeron-Pomeron interactions and photon-Pomeron interactions can be investigated. In addition we plan to participate in the SPIN physics program of STAR.

Analyzing the large amount of data accumulated with the STAR detector is a formidable challenge. New concepts need to be developed and tested. The Grand Challenge Initiative is contributing to the data management design of the RHIC Computing Facility and we plan to implement a STAR data analysis center in collaboration with NERSC.

CERN/RHIC Physics

The collisions of the heaviest nuclei at the highest energies (Pb ions at the SPS, Au ions at RHIC) are expected to create systems whose space-time dynamics are qualitatively different from those of the colliding light ions studied previously. The heavy systems have significantly higher energy densities over longer time scales. The extremely large number of produced hadrons in such collisions (several thousand in a central Au-Au event at RHIC) presents a real technical challenge and a unique opportunity: nontrivial, statistically significant signals can be extracted from single events, a technique known as "event-by-event" analysis. The correlation of extreme values of several observables sensitive to the quark-gluon plasma phase transition in a single event is a powerful tool for selecting ensembles of interesting events for detailed study. An event-by-event measurement of the produced particles provides the opportunity to select events with extreme values of temperature (particle spectrum), flavor (strangeness content), collective flow (particle momentum), and size (two-particle correlations). This technique requires a large acceptance detector that can determine the momentum and identify a large fraction of the particles emitted in the collision.

NA49 is a fixed-target experiment at the SPS designed to study Pb-Pb collisions at 160 GeV/nucleon ($\sqrt{s_{nn}} = 17$ GeV). Its goal is to simultaneously measure many hadronic signals that are thought to be sensitive to the quark-gluon plasma. To perform event-by-event analysis, it measures and identifies almost all charged particles in the forward half of phase space and carries out detailed ensemble measurements of all the single-event observables as well as strange particle decays, two-particle correlation functions, flow, and other hadronic observables.

STAR is a collider experiment at RHIC designed to study Au-Au collisions at $\sqrt{s_{nn}} = 200$ GeV. Its goal is similar to NA49's, to simultaneously measure many hadronic signals. To perform event-by-event analysis, it will measure and identify almost all charged particles over two units of rapidity, centered at mid-rapidity. In addition, at RHIC there is a high rate of hard processes. Hard-scattered partons are predicted to be sensitive to the medium through which they propagate. The process can be calculated in perturbative quantum chromodynamics. The study of high transverse momentum particles and jets as a function of energy and mass of the colliding system may also be an attractive experimental approach to identify the presence of quark matter.

Bevalac/AGS Physics

From the study of the hadronic signals of nuclear collisions with 4π detectors, like the EOS TPC, a rather simple picture is emerging, compatible with the formation of a single source that seems to show a high degree of thermalization and flow in the final state. Part of the flow pattern is established early by geometry and compression (directed flow), the other part is dominated by compression and expansion (radial flow). A careful and systematic comparison of data with microscopic models will lead to a better understanding of in-medium effects and the nuclear matter equation of state. Experiment E895 continues these studies in the AGS energy region with the focus on the study of flow and strange particle production.

Experiments

EOS TPC at the AGS (E895)

E895 is a major new experiment at the Brookhaven National Laboratory (BNL) designed to carry out a systematic and exclusive measurement of the energy and mass dependence of particle production, correlations, collective flow effects, and strangeness production in Au + Au collisions. Theoretical studies suggest maximum baryon density, as high as eight times normal nuclear matter density, is achievable in central Au+Au collisions between 2 and 10 A GeV beam energies. Therefore, E895 extends the physics program started at the Bevalac to understand the collision dynamics and obtain information on the nuclear matter equation of state. Additionally, E895 will study the change of medium effects since the baryon densities are high enough to alter the masses and widths of hadrons, which in turn, could indicate the occurrence of chiral symmetry restoration or the formation of baryon rich Quark Gluon Plasma.

The experimental arrangement consists of the EOS Time Projection chamber placed in a large 1 Tesla dipole magnet and the MUSIC detector positioned downstream of the TPC. The detectors are located in the MPS area of the Alternating Gradient Synchrotron (AGS) heavy ion facility. E895 was made operational and, in December 1995, had sucessfully recorded data using 2 and 4 A GeV Au beams. High statistics were obtained with an Au target, and less with Ag, Cu and Be targets. During the second run in November 1996 data was recorded at 6 and 8 A GeV using the same targets. A complete offline data analysis is underway at LBNL utilizing the Parallel Distributed Scientific Farm (PDSF) at NERSC, as well as at other member institutions.

NA49 at the SPS

NA49 is a large acceptance experiment based on a set of Time Projection Chambers. Particle identification is performed primarily by the measurement of dE/dx in the relativistic rise regime (leading to TPCs that are 3.6 m deep), supplemented by time-of-flight over a part of phase space. Event characterization for triggering is performed by forward calorimetry.

NA49 completed its construction phase and began taking data with the full complement of detectors in Fall 1995. Since then approximately 2 million lead-lead collisions at 158 GeV/nucleon and 1 million proton-proton collisions at 158 GeV/c have been recorded, comprising a data set of about twenty terabytes.

In order to extract the most interesting volume-dependent effects in nucleus-nucleus collisions, NA49 data on central collisions of lead ions are compared to NA35 data on central collisions of sulphur ions at about the same energy (200 GeV/nucleon). NA49 finds that transverse energy production per participant nucleon increases slightly for the lead collisions, indicating a somewhat higher stopping. The rapidity distributions of primordial protons show the same effect. Produced particle multiplicities (total negative hadrons, which are mostly pions, and neutral and charged kaons) scale roughly with the number of participants. On the other hand, transverse mass spectra show an increase of inverse slope with the mass of the particle, which is indicative of increased radial flow for lead compared to sulphur collisions. Thus, the picture that emerges from transverse energy measurements and inclusive spectra from central collisions of lead ions compared to that of sulphur ions is one of somewhat greater stopping, with the additional available energy going into increased radial flow, while the strangeness enhancement appears to be about the same.

NA49 has also found flow effects in medium impact parameter collisions of lead ions. By means of techniques developed at the Bevalac to study flow phenomena, directed and elliptic flow could be identified. This apparent memory by the system of the initial reaction geometry is of great interest to the theoretical community.

STAR at RHIC

The purpose of STAR (Solenoidal Tracker at RHIC) is to discover the Quark Gluon Plasma, a new state of matter which hasn't existed in the universe since a few microseconds after the Big Bang. RHIC will provide colliding beams of gold ions at center-of-mass energies ranging from about 50 GeV up to a maximum of 200 GeV per nucleon. Other beam combinations are possible. STAR's goal is similar to NA49's; to simultaneously measure many hadronic signals of the QGP resulting from ultra-relativistic collisions. But STAR is expected to explore nuclear collisions with energy densities that are much higher than are available at CERN. STAR will be able to perform event-by-event analysis, it will measure and identify virtually all charged particles over two units of rapidity (centered at mid-rapidity), and it will do an excellent job of characterizing high p_t particles and jets that are the result of hard-scattered partons.

The STAR detector will consist of a Time Projection Chamber (TPC) and Silicon Vertex Tracker located inside a 5.2-m-diameter solenoidal magnet to provide tracking, momentum analysis, and particle identification using the dE/dx technique. The trigger detector systems include a central scintillator barrel around the TPC, vertex position detectors near the beamline just outside the magnet, and calorimeters located in the region of the beam insertion magnets to selectively veto events according to the number of spectators. An electromagnetic calorimeter to trigger on transverse energy and measure jet cross-sections is being added. In addition, two forward time projection chambers are being built by the Max Planck Institute (Munich). The forward TPCs will extend the detector's angular coverage from 2 units of pseudorapidity up to approximately 4.

The LBNL group is focusing on tracking, momentum analysis and identification of the 2000-3000 charged particles expected within approximately ±1 unit of pseudo-rapidity at mid-rapidity in the most violent central collisions at RHIC. The tracking, momentum analysis and particle identification will be performed in the cylindrically symmetric TPC located inside a solenoidal magnet which was designed, constructed, and tested at LBNL and is now at BNL.

In parallel with the construction effort the software and analysis framework for STAR is being developed. Since the RNC group has major responsibility for the main TPC in STAR, we are presently focusing on the analysis software for the TPC detector. Based on the extensive experience with TPC analysis gained from EOS, NA35, NA36, and NA49, we are working on a complete analysis chain that will be able to extract physics results from the raw data.

An additional development has been the move of the National Energy Research Scientific Computing Center (NERSC) to LBNL. NSD scientists have taken a lead role in working with NERSC to provide for the evolution of NERSC in a direction that would provide needed and appropriate capabilities for the RHIC community (and others in the nuclear and high energy communities). These efforts include leadership of the Grand Challenge Proposal to ER/MICS and strong involvement in the development and utilization of the PDSF processor farm that was moved from the SSC Lab to NERSC.

In 1997 two important tests of the STAR TPC took place. In the first test, a TPC sector was operated in the laboratory together with its associated read-out electronics. In the second test, the fully instrumented sectors were mounted in the TPC field cage and tested with cosmic rays and laser tracks. Both of these tests were extremely successful, demonstrating the operation of the various components of the system and verifying that essential specifications such as noise, resolution and two-track separation can be met.

Following completion of the system and cosmic-ray tests, the TPC was shipped by air from LBNL to Brookhaven National Laboratory (BNL) in early November 1997. The TPC is now being prepared for further testing at BNL and eventual integration with the other components of the STAR detector.

The development phase for the TPC readout electronics is essentially complete. In 1997 the custom integrated circuits (pre-amps, amplifiers, SCAs and ADCs) were ordered and a substantial fraction of the boards have been fabricated. Installation of much of the electronics will be completed in 1998.

At LBNL development has continued for software that performs cluster finding, tracking and particle identification; this transforms raw data into information that can be used for the physics analysis.

Development

Micro TPC Vertex Detector

We are developing a new Micro TPC vertex detector that will be capable of tracking in the high track density environments which will be encountered in the STAR experiment at RHIC and in the ALICE experiment at LHC. This detector can handle track densities of 10 tracks/cm^2, approaching the capabilities of silicon devices. It has, however, the important advantage that it is essentially massless in comparison. This greatly reduces problems due to multiple scattering and secondary interactions, which is of utmost importance for vertex detectors. This technology could provide a significant improvement over silicon in these experiments particularly at low p_t where exciting results have been predicted for heavy ion collisions. The Micro TPC will use micro-strip gas chambers (MSGCs) to read out the signal. The fine pitch of these devices is well matched to the low diffusion that can be achieved with a short drift distance in dimethyl-ether (DME). This combination makes it possible to achieve much better two-track resolution than has been possible with other TPCs. We have demonstrated that electrons can be drifted in DME over the planned drift distance of 15 cm without significant attenuation. We have also produced a MSGC on a silicon amplifier chip and demonstrated suitable operation.

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